

Upgraded experiments with super neutrino beams

Patrick Huber

University of Wisconsin – Madison

based on

V. Barger, PH, D. Marfatia and W. Winter, hep-ph/0610301

Brookhaven National Laboratory

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Outline

- Status quo
- Origin of neutrino mass
- Key measurements
- Neutrino oscillation
- Experimental strategies
 - T2KK
 - WBB
 - NO ν A*
- Comparison & robustness
- Summary

Status quo

- Conversion of ν_e from the Sun into $\nu_\mu + \nu_\tau$
- Disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of ~ 200 km
- Disappearance of ν_μ from the Atmosphere
- Disappearance of ν_μ from a neutrino beam
- No disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of ~ 1 km

Status quo

A common framework for all the neutrino data is oscillation.

- $\Delta m_{21}^2 \sim 8 \cdot 10^{-5} \text{ eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m_{31}^2 \sim 2.5 \cdot 10^{-3} \text{ eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \lesssim 0.15$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2.5 \cdot 10^{-3} \text{ eV}^2} \sim 0.05 \text{ eV}$$

but we currently do not know which neutrino is the heaviest.

Status quo

Quarks

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

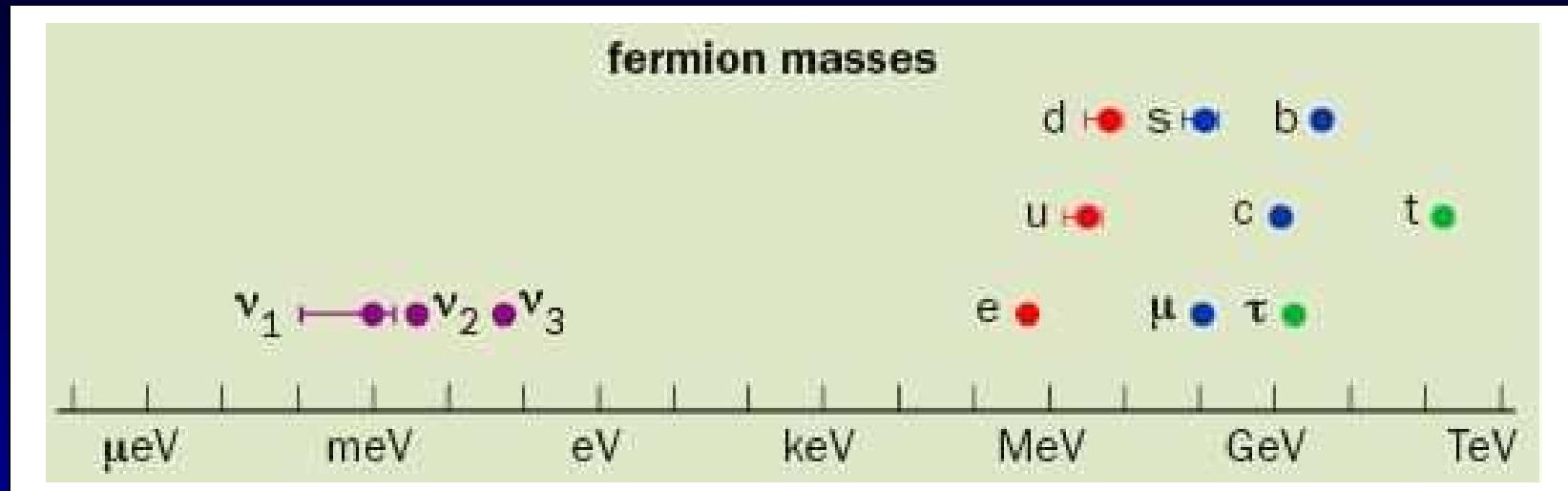
Neutrinos

$$U_\nu = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

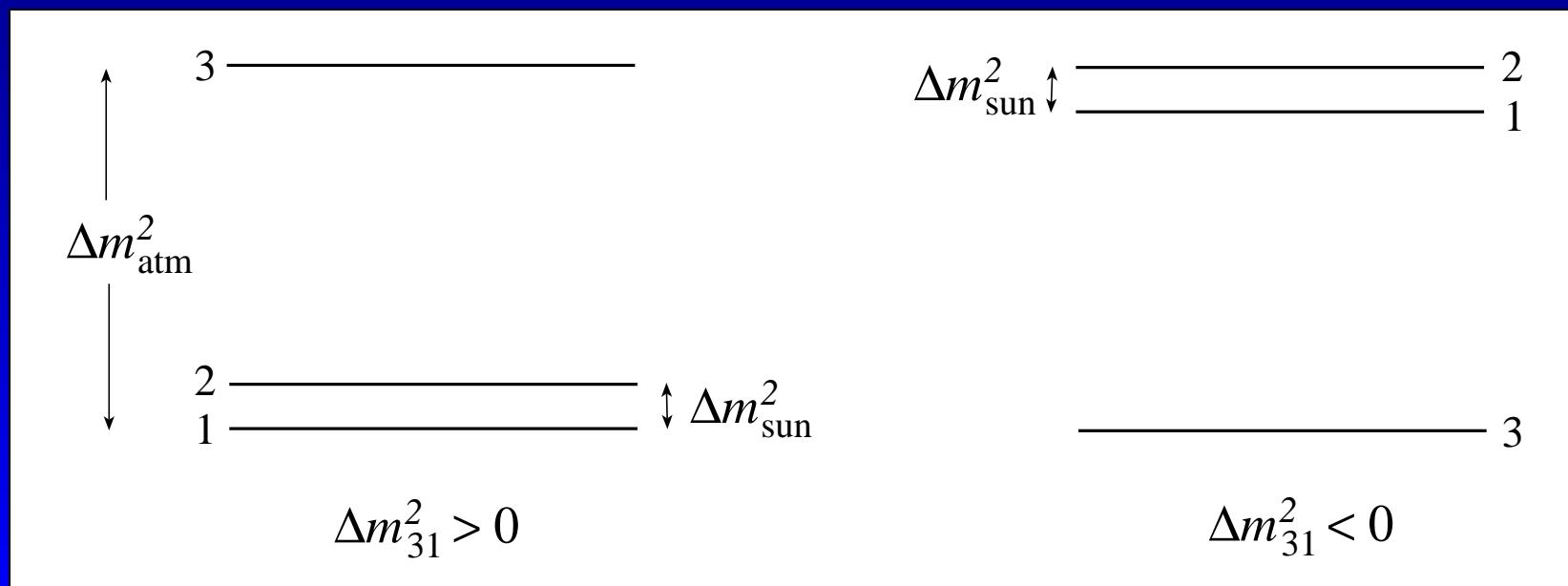
Why are neutrino mixings so large?

Status quo

Mass hierarchy in the SM



What makes neutrinos so much lighter?



Origin of neutrino mass

Neutrinos in the Standard Model (SM) are strictly massless, *ie.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable.

Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model.

Origin of neutrino mass

The SM is an effective field theory, *ie.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda} (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is the most sensitive probe for new physics at high scales

Origin of neutrino mass

One example is the seesaw mechanism

$$\mathcal{L}_\nu = m_D \overline{\nu_L} N_R + \frac{1}{2} m_R \overline{N_L^c} N_R + h.c$$

N_R is a heavy right handed neutrino, *ie.* a singlet under the SM gauge group.

The light neutrino mass is given by

$$m_\nu \simeq \frac{m_D^2}{m_R}$$

Identifying $m_D \sim 100$ GeV and $m_R \sim m_{GUT} \sim 10^{15}$ GeV yields $m_\nu \simeq 10^{-2}$ eV

Origin of baryons

At the same time N_R can provide a mechanism for creating the observed tiny surplus of matter over anti-matter.

Leptogenesis requires the temperature of the Universe to be high enough that there is a thermal population of N_R . Their subsequent out-of-equilibrium decays are a new source of CP violation and lepton number

$$\Gamma(N_R \rightarrow LH) - \Gamma(N_R \rightarrow \bar{L}H^*) \neq 0$$

which later on is converted to baryon number by non-perturbative processes.

Key measurements

In the context of GUT scale right handed neutrinos it is very difficult to establish a one-to-one correspondence between high and low-energy observables.

A given model, however, usually has generic predictions for low energy observables. Therefore studying neutrinos allows to gain considerable insight into phenomena which otherwise would be inaccessible.

Colliders can not probe this kind of physics, since any effects in scattering amplitudes are suppressed by m_{GUT} , at LHC this would be effects of $\mathcal{O}(10^{-10})$!

Key measurements

Case	Texture	Hierarchy	$ U_{e3} $	$ \cos 2\theta_{23} $	Solar Angle
A	$\frac{\sqrt{\Delta m_{13}^2}}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	Normal	$\sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}}$	$\sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}}$	$\mathcal{O}(1)$
B	$\sqrt{\Delta m_{13}^2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Inverted	$\frac{\Delta m_{12}^2}{ \Delta m_{13}^2 }$	$\frac{\Delta m_{12}^2}{ \Delta m_{13}^2 }$	$\mathcal{O}(1)$
C	$\frac{\sqrt{\Delta m_{13}^2}}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$	Inverted	$\frac{\Delta m_{12}^2}{ \Delta m_{13}^2 }$	$\frac{\Delta m_{12}^2}{ \Delta m_{13}^2 }$	$ \cos 2\theta_{12} \sim \frac{\Delta m_{12}^2}{ \Delta m_{13}^2 }$
Anarchy	$\sqrt{\Delta m_{13}^2} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	Normal	> 0.1	–	$\mathcal{O}(1)$

Caveat: Assumes diagonal lepton mass matrix!

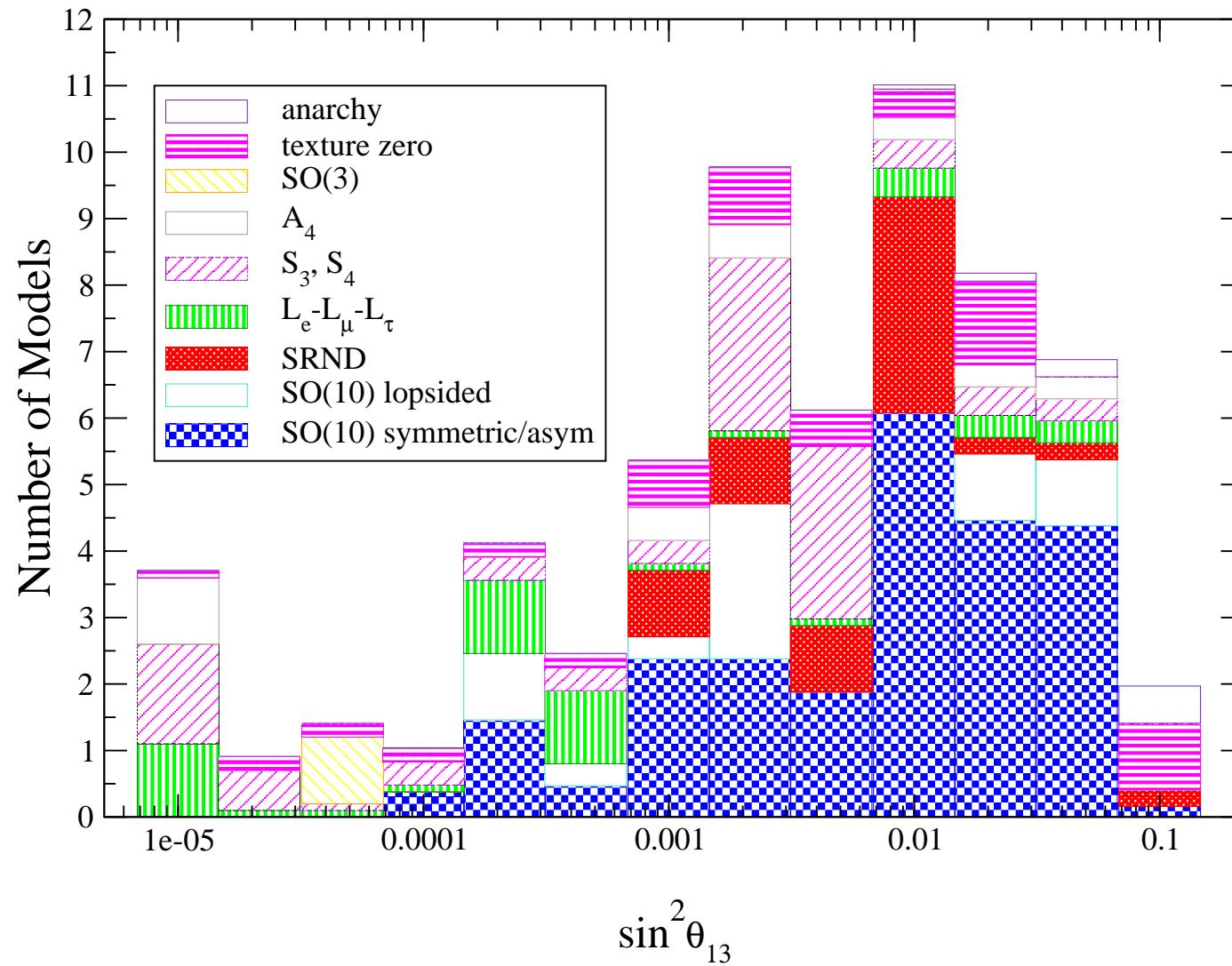
Key measurements

The most sensitive low energy observables are

- Majorana vs Dirac mass – $0\nu\beta\beta$
- Absolute m_ν – Katrin, Cosmology
- How large is θ_{13} ? – Oscillation
- Which one is the heaviest neutrino? – $0\nu\beta\beta$, Katrin, Oscillation
- Is θ_{23} maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation

One example

Predictions of All 63 Models



Albright, Chen, 2006.

Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by U_ν , thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sum_{ij} U_{\alpha j} U_{\beta j}^* U_{\alpha i}^* U_{\beta i} e^{-i \frac{\Delta m_{ij}^2 L}{2E}} \sim \sin^2 2\theta \sin^2 \frac{\Delta m_{ij}^2 L}{4E}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.

Neutrino oscillations – CP viol.

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \delta$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$, which is only available in beam experiments.

Neutrino oscillation – matter

The charged current interaction of ν_e with the electrons creates a potential for ν_e

$$A = \pm 2\sqrt{2}G_F \cdot E \cdot n_e$$

where + is for ν and – for $\bar{\nu}$.

This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

Neutrino oscillation – matter

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

$$P(\nu_\mu \rightarrow \nu_e)$$

Two-neutrino limit – $\Delta m_{21}^2 = 0$

$$\approx \frac{\sin^2 2\theta_{13}}{\sin^2 \theta_{23}} \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$P(\nu_\mu \rightarrow \nu_e)$$

Three flavors – $\Delta m_{21}^2 \neq 0$

$$\begin{aligned} & \approx \sin^2 2\theta_{13} \quad \sin^2 \theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2} \\ & \pm \alpha \sin 2\theta_{13} \quad \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \alpha \sin 2\theta_{13} \quad \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \alpha^2 \quad \cos^2 \theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

$$P(\nu_\mu \rightarrow \nu_e)$$

Small quantities – $\alpha := \Delta m_{21}^2 / \Delta m_{31}^2$ and $\sin 2\theta_{13}$

$$\begin{aligned} & \approx \frac{\sin^2 2\theta_{13}}{\sin^2 \theta_{23}} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2} \\ & \pm \frac{\alpha \sin 2\theta_{13}}{\sin \delta \sin 2\theta_{12} \sin 2\theta_{23}} \quad \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \frac{\alpha \sin 2\theta_{13}}{\cos \delta \sin 2\theta_{12} \sin 2\theta_{23}} \quad \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \frac{\alpha^2}{\cos^2 \theta_{23} \sin^2 2\theta_{12}} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

Eight-fold degeneracy

- intrinsic ambiguity for fixed α

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- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow \mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

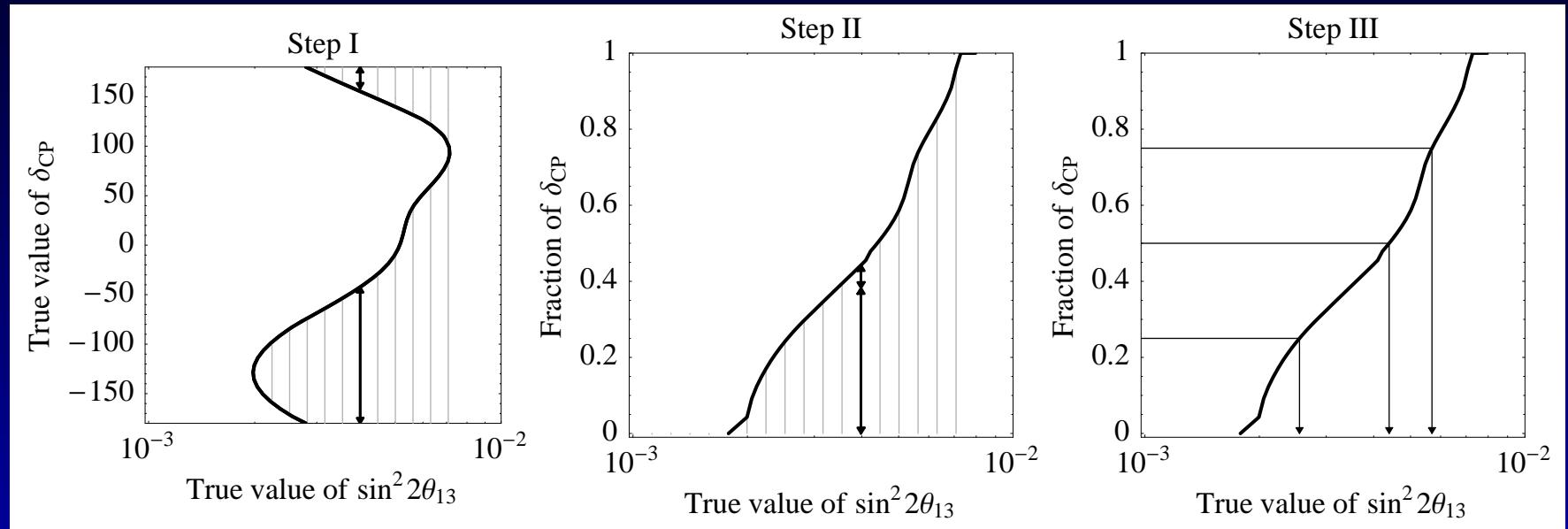
Setups

detector mass [Mt] \times target power [MW] \times running time [10^7 s].

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	\mathcal{L}
NO ν A*	3	3	1 (ν)	810	Liquid argon TPC	100	1.02
WBB	5	5	1 (ν) + 2 ($\bar{\nu}$)	1290	Water Cherenkov	300	7.65
T2KK	4	4	4 (ν)	295+1050	Water Cherenkov	270+270	17.28

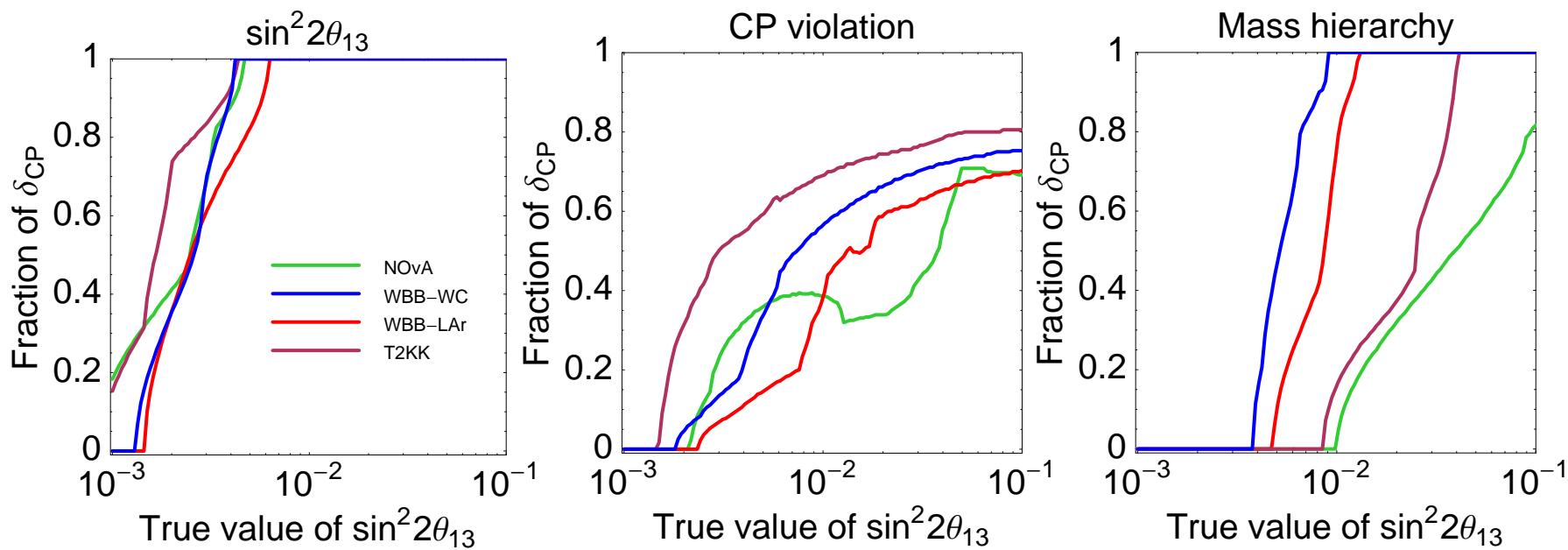
- 5% systematics for all setups
- LArTPC based on numbers from B. Fleming
- WBB-WC based on Yanagisawa *et al.*
- T2KK performance based on LOI
hep-ex/0106019
- NuMI fluxes from M. Messier's website

CP fraction



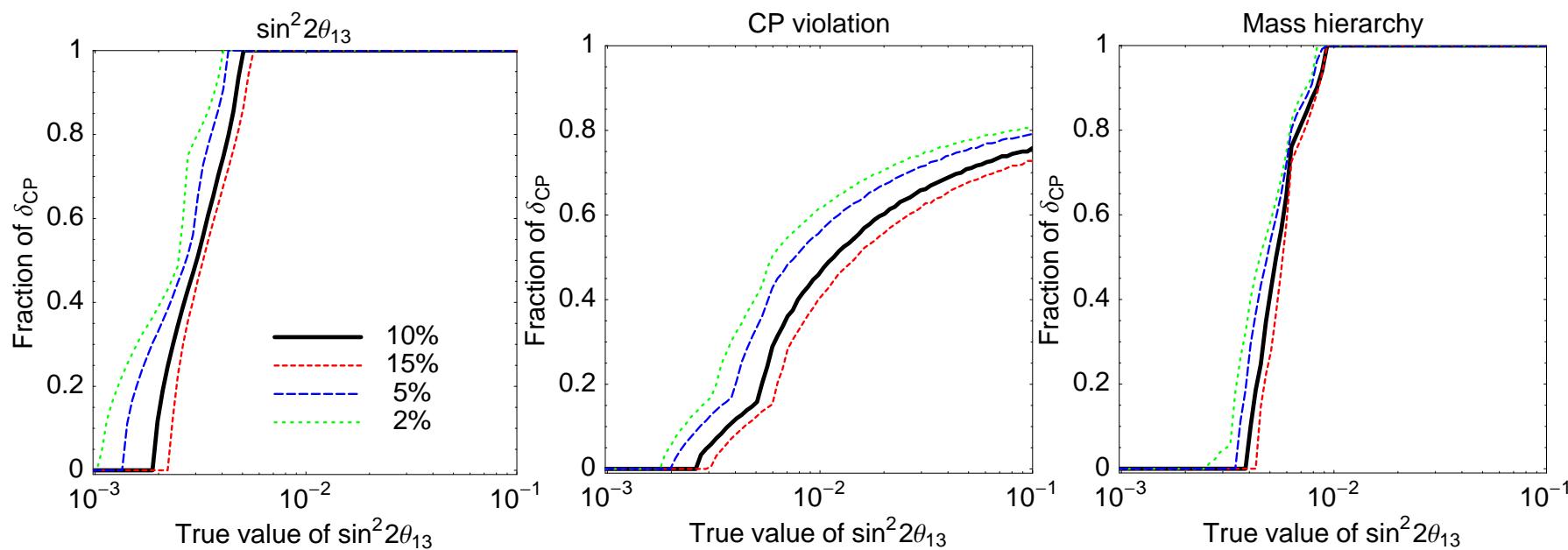
- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF = 0, best case

Comparison



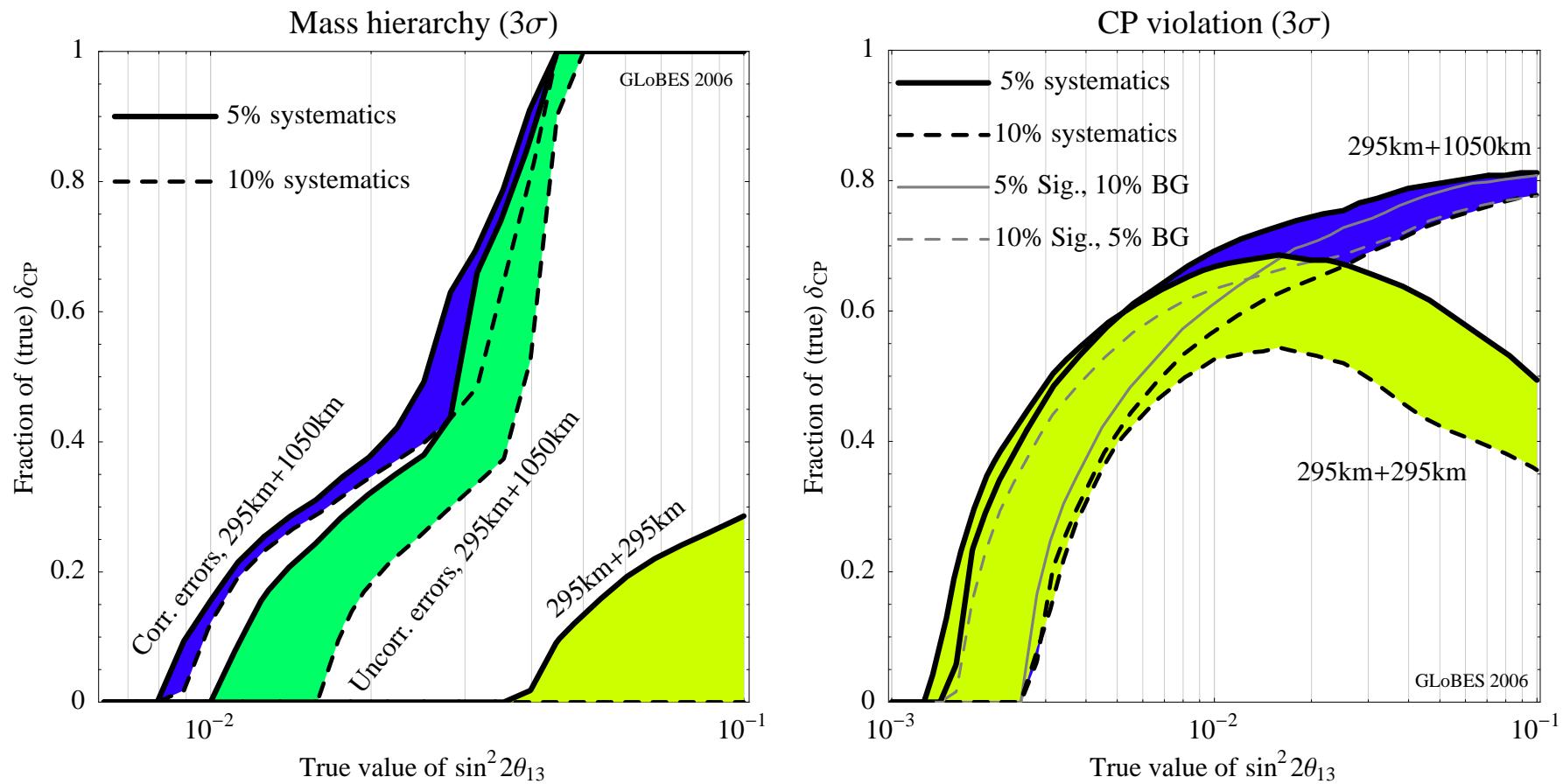
- $\sin^2 2\theta_{13}$ performances are very similar
- T2KK clearly best for CPV
- WWB clearly best for mass hierarchy

WBB

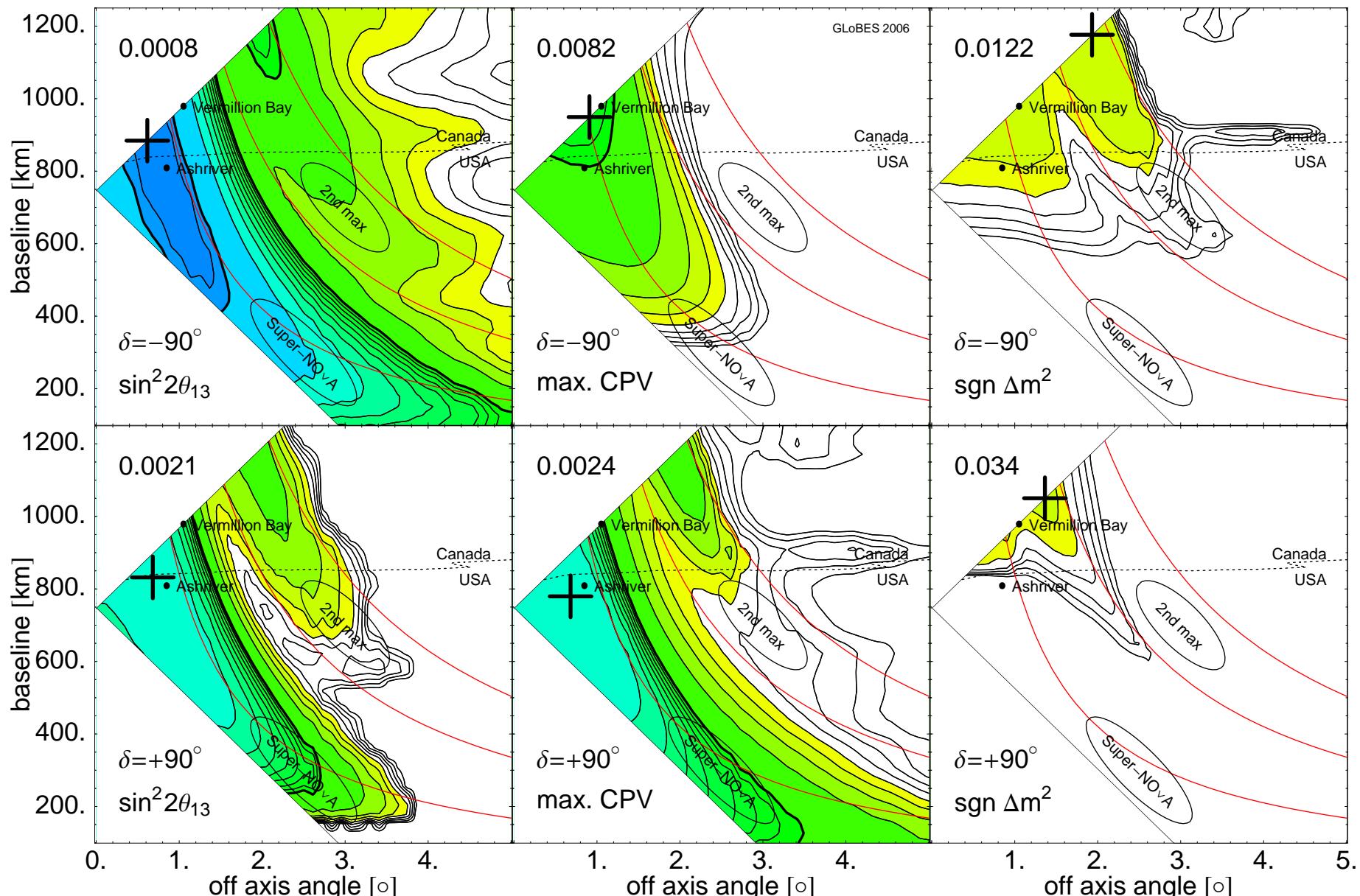


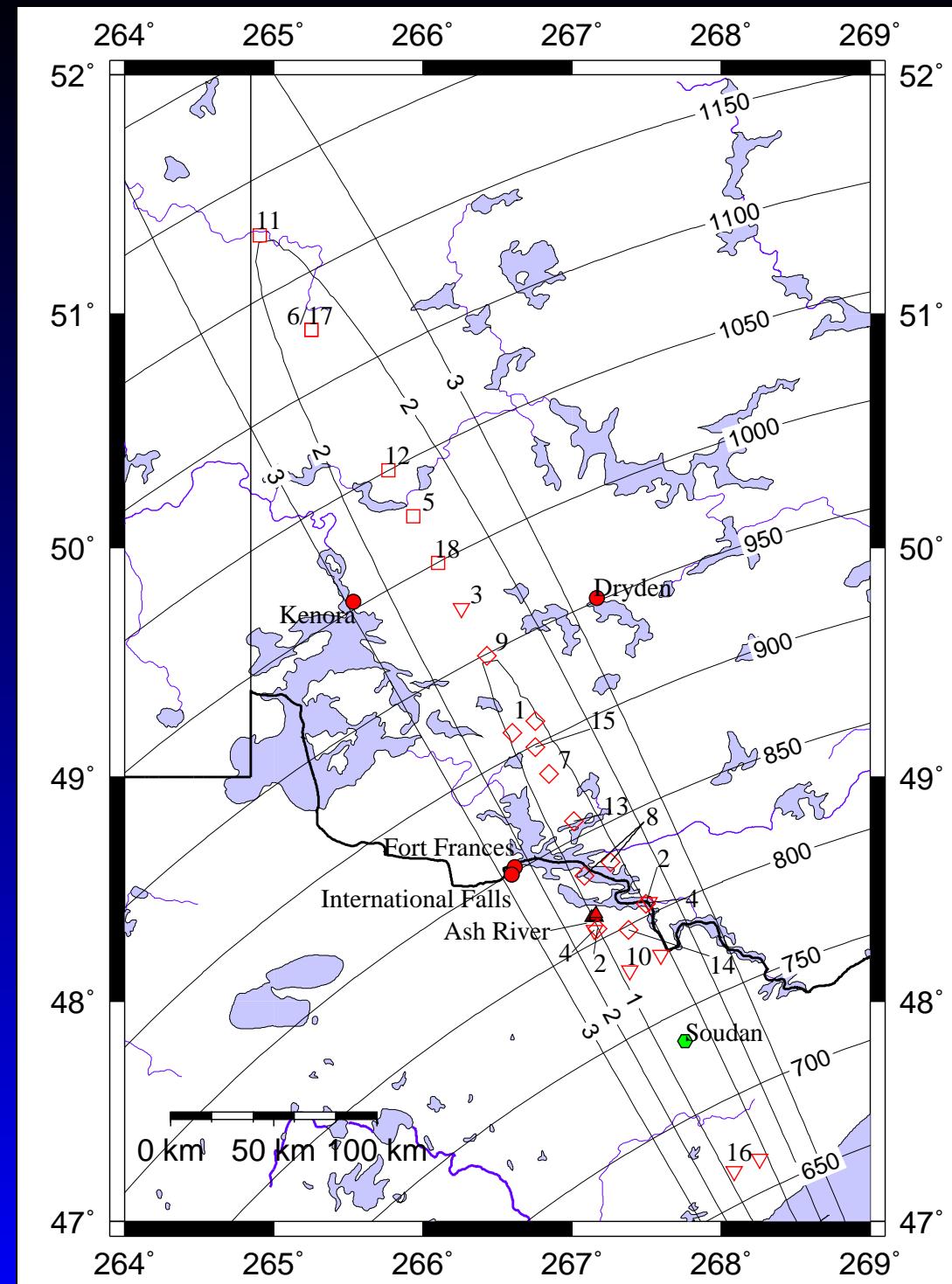
V. Barger , M. Dierckxsens, M. Diwan, PH, C. Lewis, D. Marfatia,
B. Viren, Phys.Rev.D74:073004,2006.

T2KK

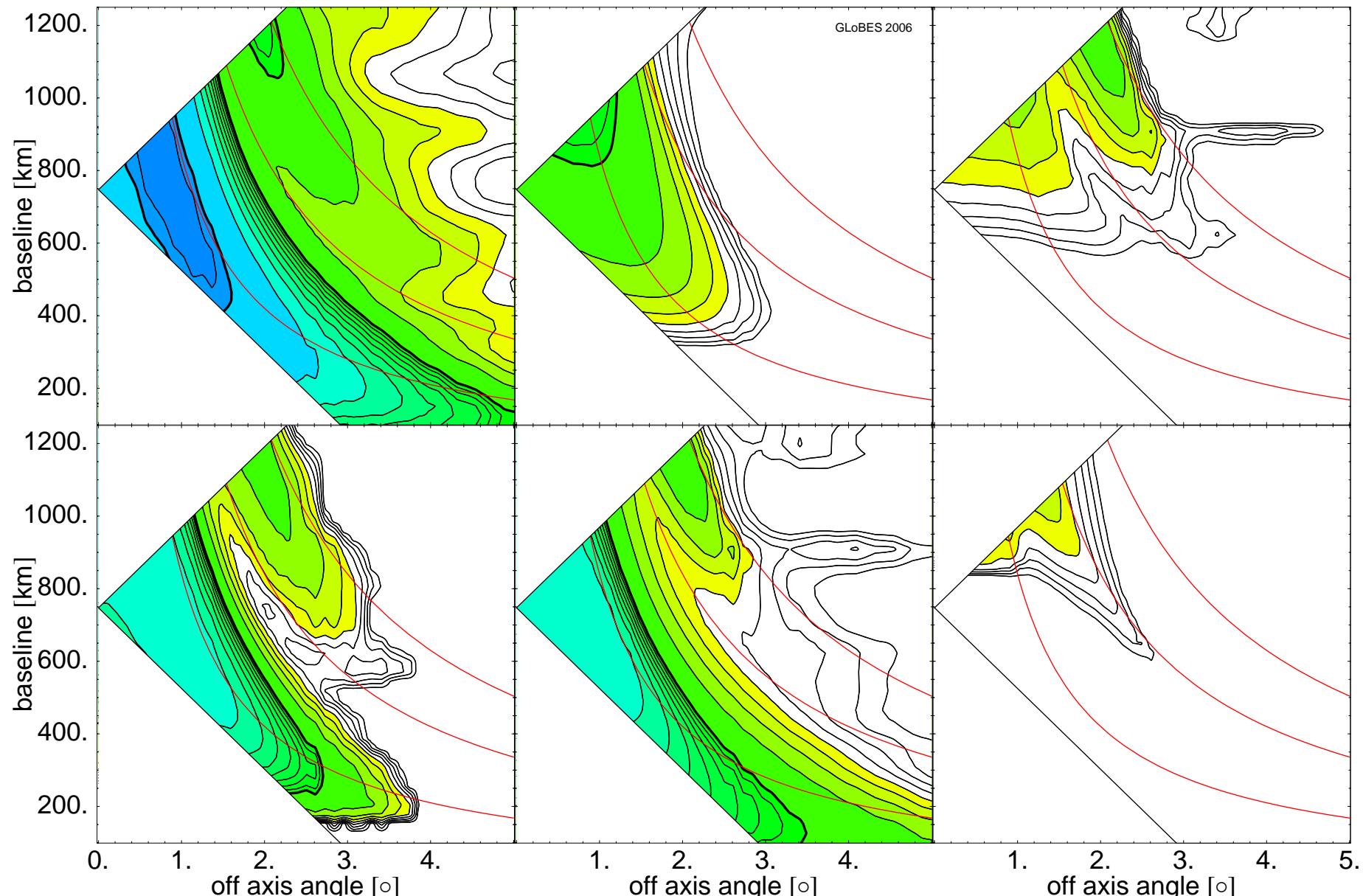


Where to put NO ν A*

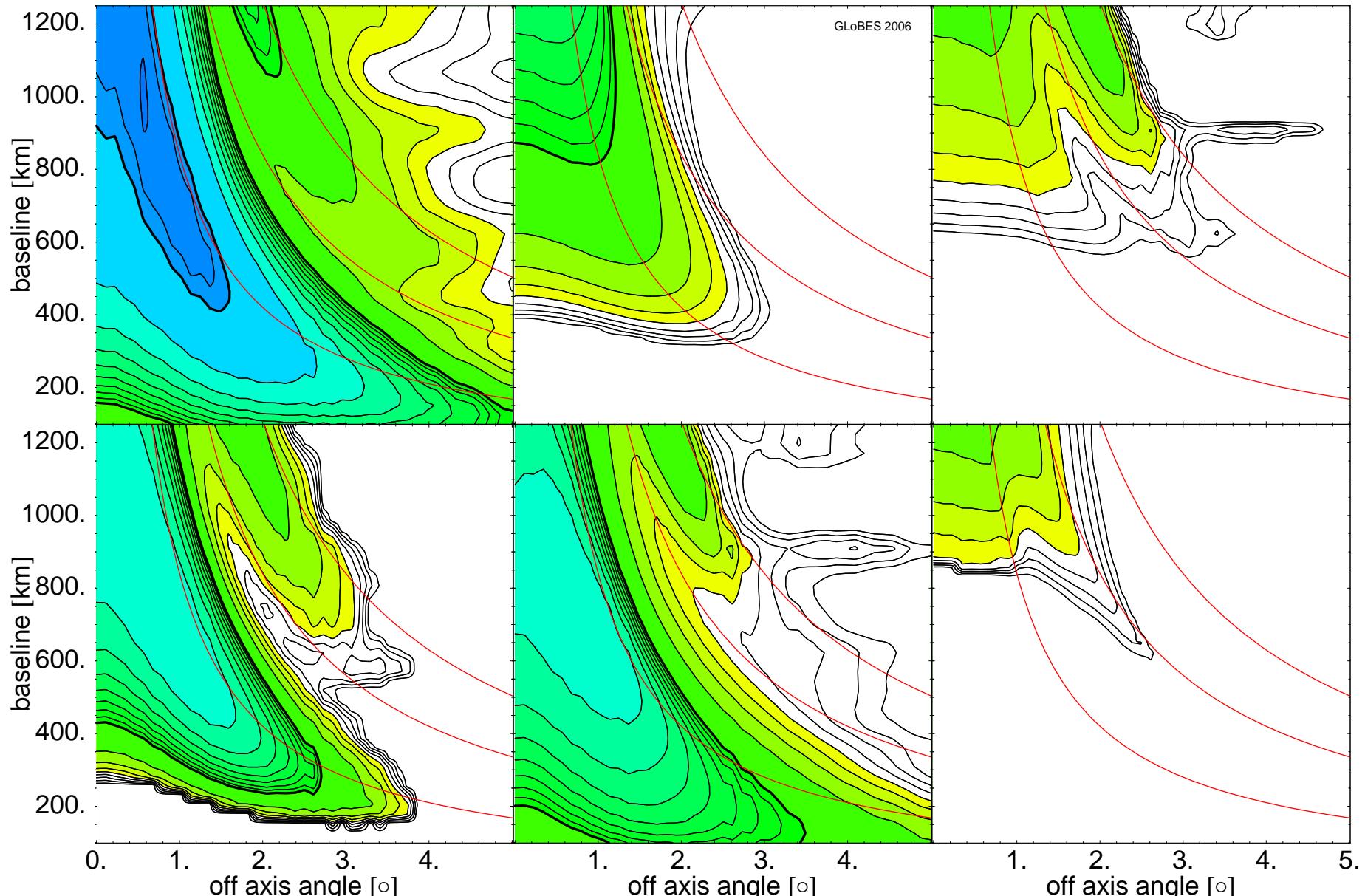


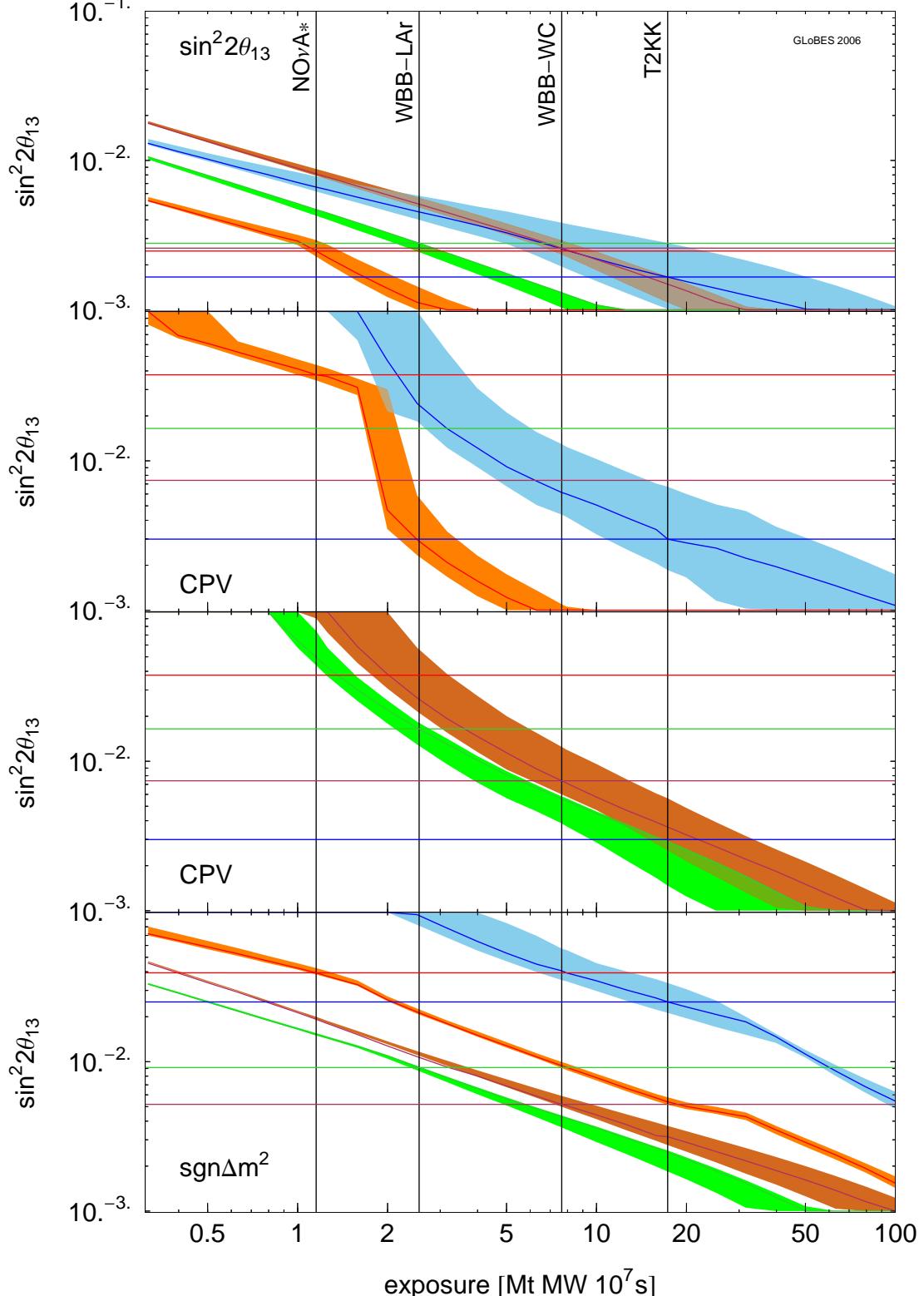


On vs off-axis

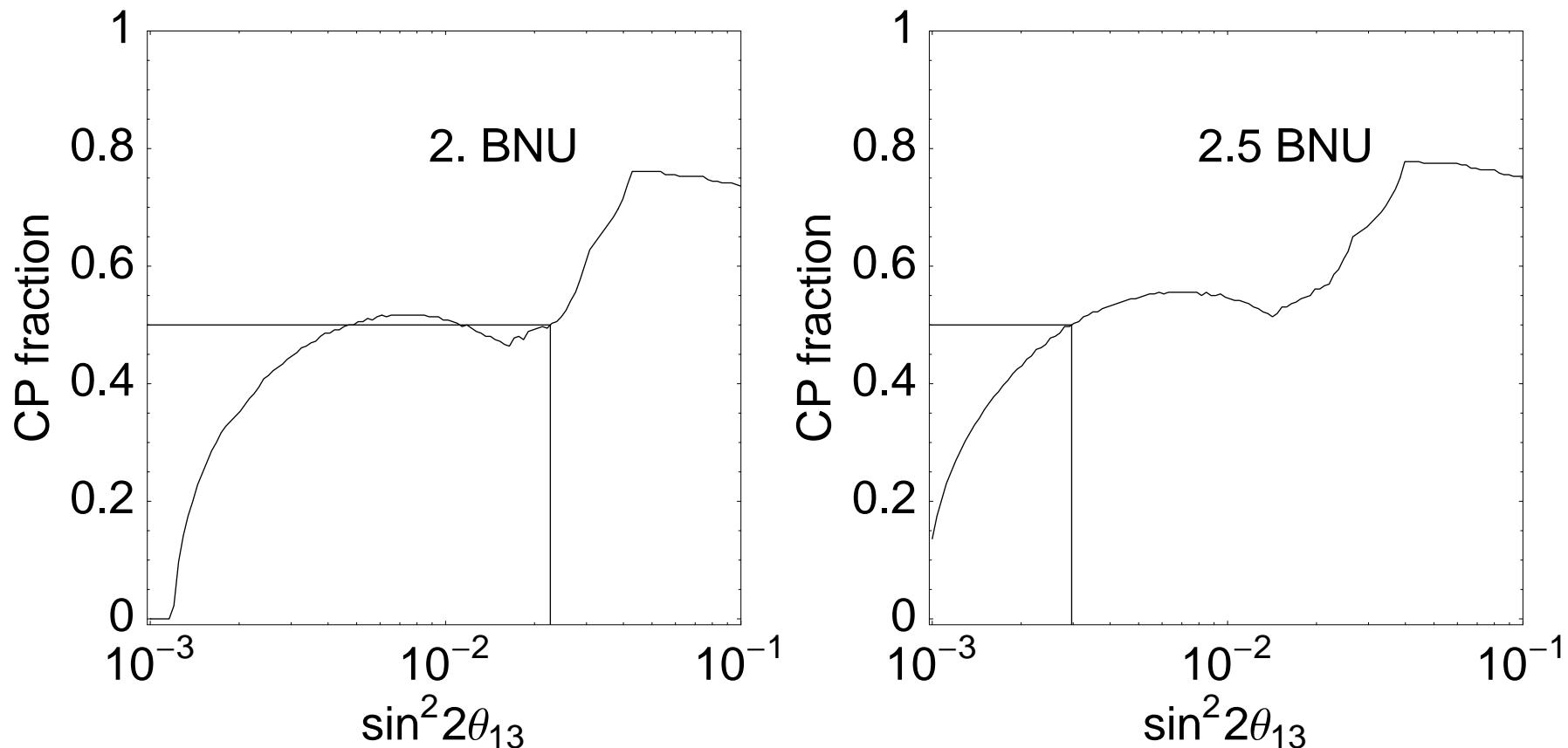


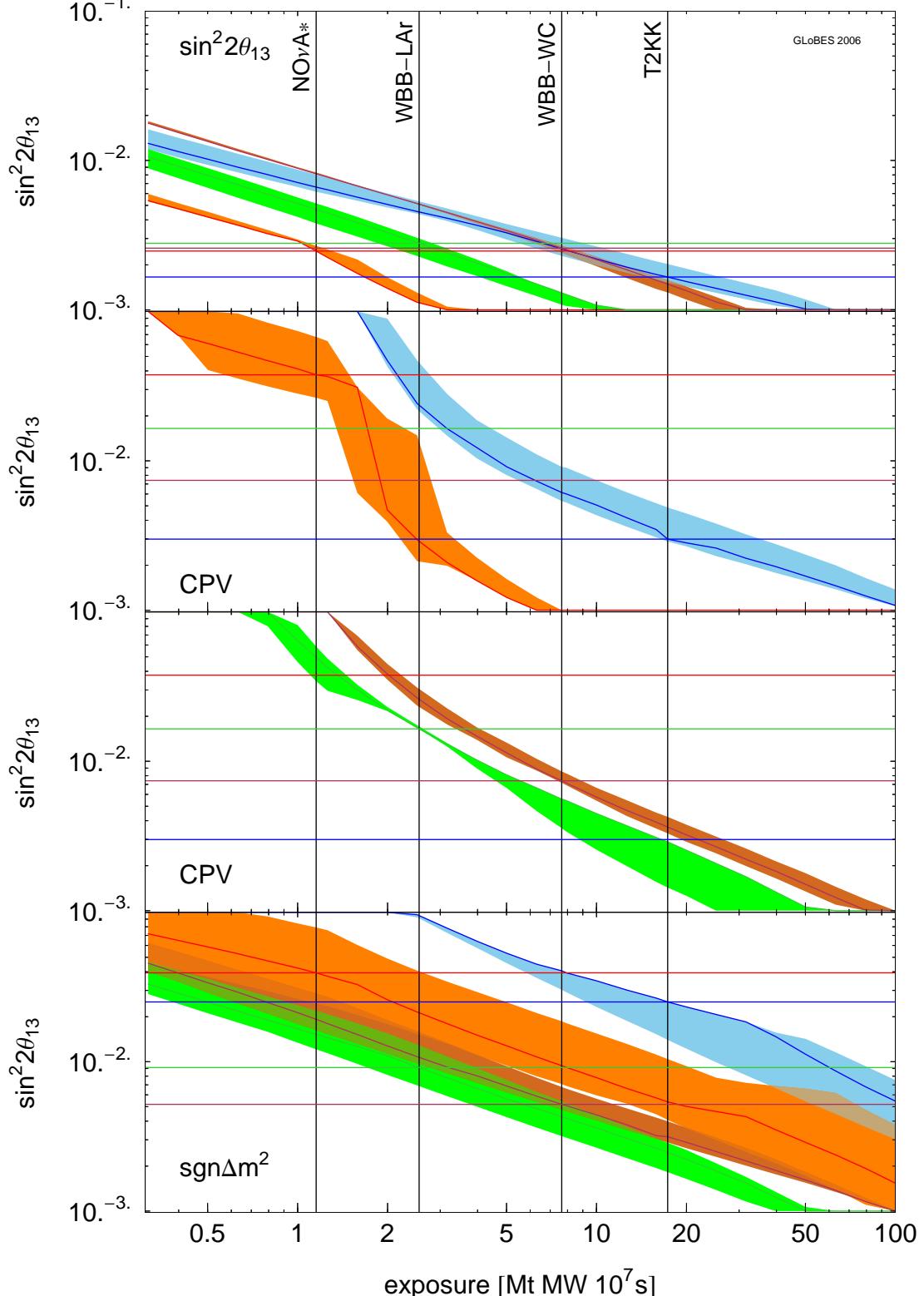
On vs off-axis

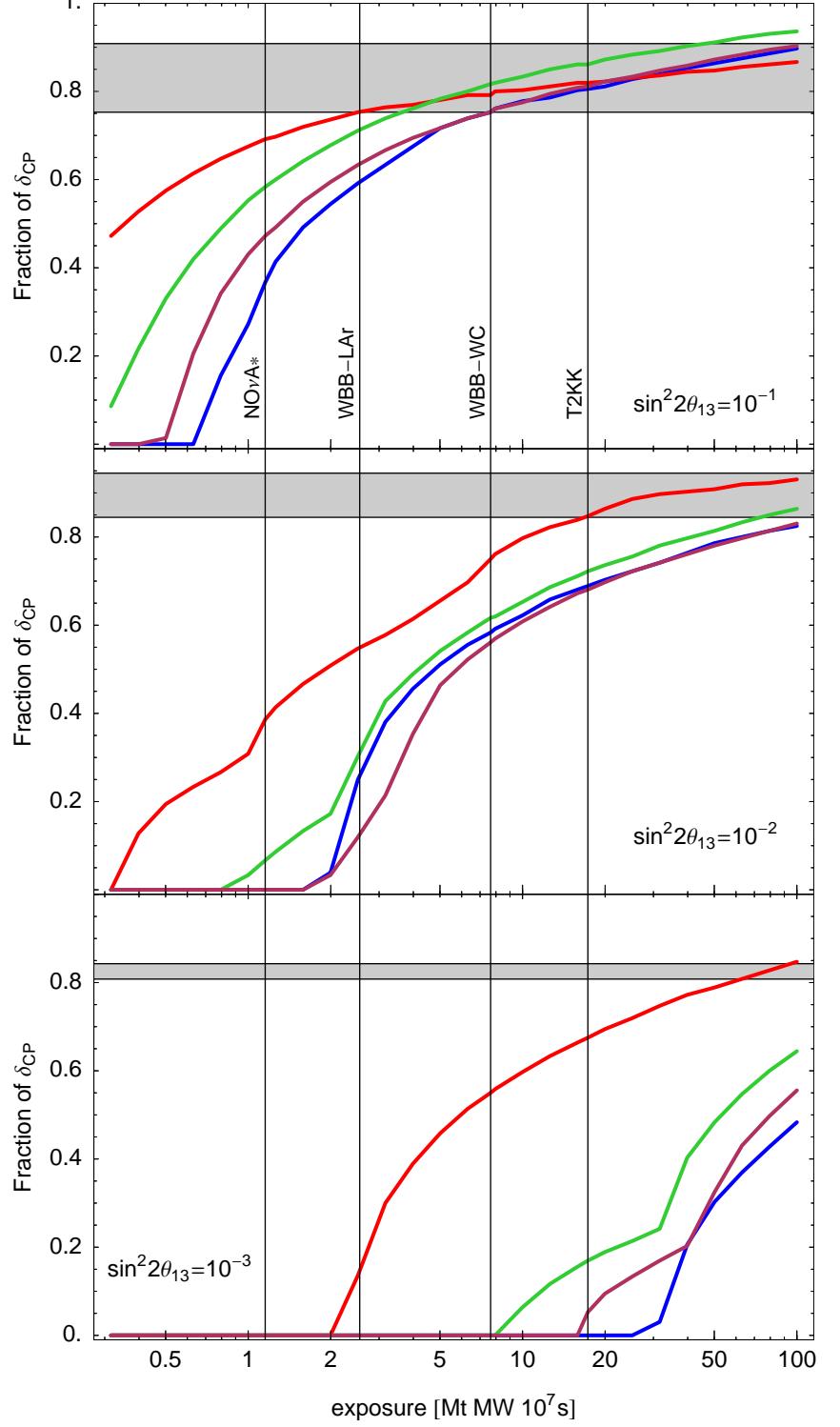




The Jump







Summary

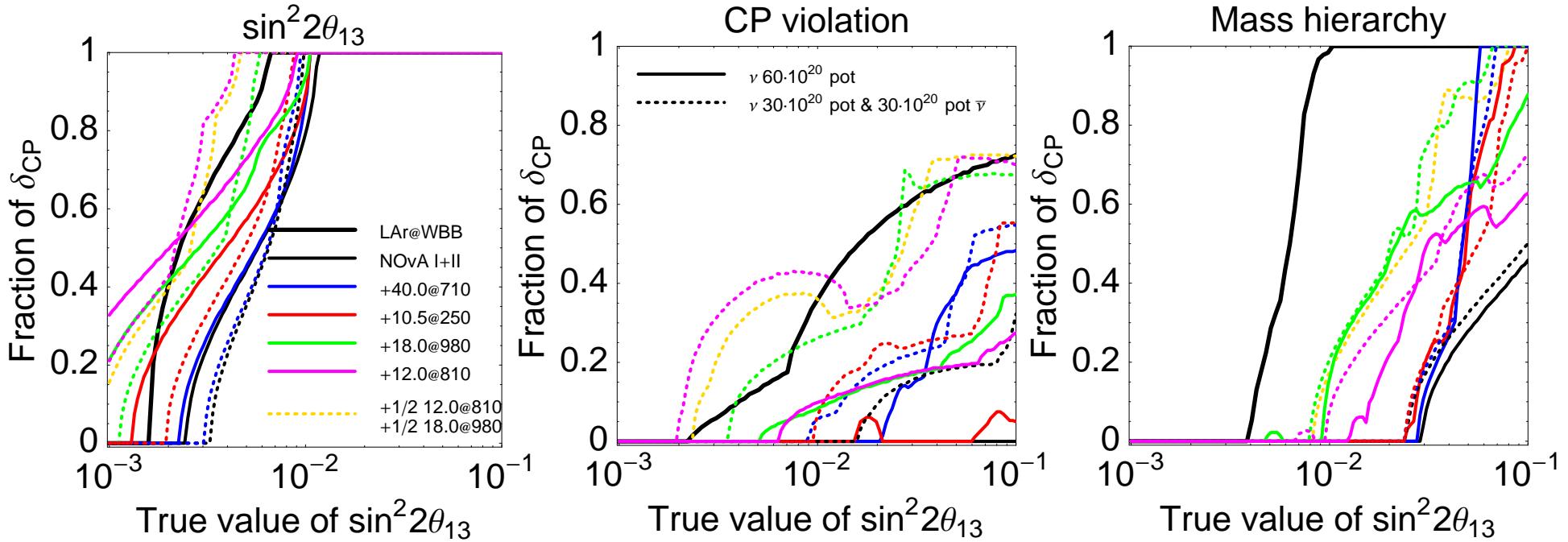
- Neutrinos have mass
- New Physics
- Many candidates
- Oscillation can provide many of the key measurements
- Complementary to the energy frontier

Summary

- Exposure is the key factor – money and physics
- Detector technology plays a big role
- Off vs On-axis decision requires careful analysis
- NO ν A* can be a competitive experiment
- Short distances (< 500 km) are disfavoured
- Every strategy requires MW beams, 0.1 Mt detectors, 10 years of running

500,000,000 \$\$

More NO ν A options



The Jump

